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Experimental Rig for Measuring Lubricant Film Thickness in Rolling Bearings

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Abstract. Electrical capacitance has been applied in the past for measuring the lubricant film thickness in rolling element bearings. The main difficulty arises from the fact that the measured capacitance is a combination of the capacitances of many rolling elements, which come in contact with both the inner and outer rings. Besides, the capacitance of the Hertzian contact itself and the surrounding area must also be separated. It results in a complex system which, in order to be solved for the film thickness at a particular location on the bearing many approximations have to be made. In the present study the authors use an experimental rig in which the capacitance of a single ball can be isolated. Moreover the capacitance of the ball – inner ring and ball – outer ring contacts can be measured separately.

Introduction

Rolling element bearings are no doubt the most numerous machine elements in use. Every single machinery or piece of equipment which involves rotating parts needs bearings to support those. If one thinks only in terms of road vehicles, there are about 600 million running every year. This amounts to over 2.4 billion bearings only for the wheels, however there are many other bearings in any road vehicle. It is clear than rolling bearings are vital machine components thus their reliability and durability are of great importance for the global economy. Apart from careful choice of the material (most often steel) and manufacturing tolerances the most important factor influencing rolling bearings' durability is their lubrication. The lubricant protects the metallic surfaces from direct contact, convects away heat generated, removes un-wanted inclusions and protects against corrosion. Lubrication also plays a key role in the contact fatigue failure of rolling bearings thus evaluation of the lubrication regime and the lubricant film thickness in conditions as close as possible to those in operation, are needed.

The measurement of the thickness of the lubricant in elastohydrodynamic (EHD) contacts, characteristic to rolling elements bearings is not an easy task, given the small dimensions and the confined space available. Optical interferometry is widely used in laboratories to evaluate the film formation and measure the film thickness [1]. Refinements to this technique have allowed researchers to measure films as thin as few nanometers and made possible the study of behavior of additives and lubrication of rough surfaces [2 – 5]. The optical interferometry technique is precise and accurate but it is only suited for laboratory measurements. This is because it requires that one of the bodies is a flat disc and it is made out of a transparent material. The implications of these requirements are that the true geometry of the contact of rolling bearings and the combination of materials in bearings cannot be reproduced.

The other methods which have been used for the study of elastohydrodynamic lubrication are based on measurement of electrical properties of the contact, such as electrical resistance and capacitance. Relatively recent a technique based on ultrasound has also been devised [6]. Electrical methods were first to be used for the measurement of lubricant film thickness in EHD contacts because of their relative simplicity and because they can be employed directly on real machine elements. Many studies based on electrical methods, that allowed important progress in the

understanding of elastohydrodynamic lubrication to be made, have been published in the past [7 – 11] however only those related directly rolling bearings will be detailed here. Electrical capacitance proved suitable for measuring the lubricant film thickness firstly because it relates directly to capacitance and secondly because this relationship is an inverse proportionality, which means the method is more accurate at small thicknesses, as it is the case of the EHD films.

Wilson [12] used the capacitive method developed by Dyson et al [13] for measuring the film thickness in spherical and cylindrical roller bearings lubricated by grease. The measured capacitance was done for the contacts between all balls and both the inner and outer rings. He took into account the variation of the load with the angular position of the rotating ring and used the parallel-plate capacitor formula to extract film thickness from capacitance. Wilson recognized that the film thickness at the inner and outer rings should not be equal due to different geometry and heat flow conditions. To account for this he made the assumption that the film thickness at the outer ring contact is 20 percent larger than that at the inner ring.

Hemskerks and co-workers [14] employed a more sophisticated apparatus that was able to measure both film thickness and number of asperity contacts. From theoretical calculations they estimate that the difference between the outer and inner ring is 10 percent. They compared the percentage of metallic contact time measured by the instrument with theoretical predictions. The same instrument was used by Leever and Houpert [15] to evaluate the lubricant film thickness in a deep groove ball and a spherical roller bearing. The film thickness was extracted from measured capacitance between the outer and inner rings of the bearing using a procedure similar to that of Dyson et al [13]. They also measured the temperature of inner and outer rings and applied a correction factor to the film thickness, to allow for a drop in viscosity due to temperature increase. Their results showed that the capacitance of the unloaded zone of the bearing is significantly large especially for the smaller, ball bearing. They also revealed that a continuous film was present in the contacts even in very poor lubrication conditions (film ratio $\lambda = 0.1$). This surprising finding was explained by the deformation of the asperities of the surfaces in the contact. Their results showed a remarkable correspondence with theoretical values predicted by smooth – surfaces formulas.

Wittek et al investigated the film thickness in thrust bearings [16]. They were particularly interested by grease – lubricated bearings used in electrical machines and on how the electrical current might discharge through the film. They consider that there is a constant multiplying factor of 3.5 between the total capacitance of a contact and the capacitance of the Hertzian zone only. The film thickness is considered constant throughout the contact area and the parallel – plate capacitor formula is employed to calculate the film thickness.

In this paper an experimental rig for measuring lubricant film thickness separately for the contacts between rolling elements and inner and outer rings is presented. The film thickness is calculated from capacitance with a methodology published previously by the authors and briefly shown in the next section. Preliminary film thickness results are also shown.

Background

Some of the advantages of the capacitance method of measuring film thickness in elastohydrodynamic contacts have been mentioned in the previous section. One of the disadvantages is the number of approximations and assumptions made when extracting film thickness from capacitance measurements. These assumptions are needed because there was no way of comparing the film thickness estimated from capacitance with separate measurements. Recently, however, Jablonka et al [17] have devised a method which overcomes this shortcoming. This method was detailed in previous publications thus will only briefly summarized in this paper. The elastohydrodynamic contact under study was formed in a test rig, between the flat of a disc and a ball. The disc was made out of glass and had on the contacting surface a thin chromium layer. The ball was made out of bearing steel thus the film thickness in contact thus formed could be measured by optical interferometry. To be mentioned that the thickness of the chromium layer was greater

than that usually chosen for optical interferometry work for three reasons: to provide a conductive layer which can act as the plate of a capacitor, to provide an increase phase shift between the light rays reflected at the ball and chromium surfaces, and to enhance its wear resistance. Interference images of the whole contact were recorded in various conditions of speed and load, simultaneous with measurements of capacitance of the disc – ball system. Obviously this system comprises the capacitance of the Hertzian contact and of the region surrounding it. Measurements were carried out at rather low film thickness in order to get as large as possible values of the capacitance and because in these conditions the side lobes characteristic to EHD contacts are very shallow and therefore the Hertzian contact approaches a parallel – plate capacitor. The knowledge of central film thickness from the optical interferometry measurements allowed a much better evaluation of the contribution of the outside region to the total capacitance. It was found that at very thin films the Hertzian area capacitance dominates but as the film increases the roles reverse. At over 200 nm the ratio of outside region to Hertzian area capacitance is about 3 and increasing. Analysis of data from reference [16] by Wittek and co-workers shows that most of their film thickness exceed 200 nm, so the value of 3.5 for the ratio of outside region to Hertzian area capacitance may be justified, however to be noted that this is only valid at relatively thick films and it is not constant.

The analysis carried out in [17] has also revealed that taking the extent of out – of – contact region up to a distance, from the contact centre, where the separation between surfaces is equal to nine times the central film thickness gives good approximation to calculated film thickness. Based on the glass/steel contact measurements Jablonka et al [17] have proposed a procedure for evaluation of film thickness, from capacitance, for steel/steel contacts. According to this procedure the capacitance of the region outside the Hertzian area is calculated using Hamrock & Dowson formula for central film thickness and the dielectric constant of a non-polar lubricant, at the contact pressure, is estimated with the aid of Clausius – Mossotti formula.

Experimental rig

The film thickness at the contacts between the rolling elements and the two rings are not equal. The inner ring surface conforms relatively closely to the ball surface only in a direction perpendicular to the rolling direction. The outer ring surface on the other hand, conforms to the ball surface in both the rolling direction and a direction perpendicular to that, thus the conditions of film formation are more favourable. Another cause for the difference of the film thickness at the inner and outer rings is the heat transfer, which is bound to be different due to the arrangement of the bearing. The outer ring is attached to the housing, which is larger but stationary, while the inner ring fitted to the shaft which has a smaller mass but is rotating. As seen previously researchers make various assumptions regarding the ratio between the inner and outer ring contacts' film thickness. The present rig is able to separately measure the capacitance of the inner and out ring contacts. Moreover the capacitance of only one ball is measured, thus the procedure of evaluating film thickness from capacitance is much more simplified and thus more precise.

The bearing under test is a deep groove ball bearing 6306 with eight balls, tolerance class C3. The test bearing is attached to a rotating shaft and its outer ring is fitted to the inner ring of larger bearing via an insulating sleeve. When the shaft rotates the cage of the test bearing is held fixed. The rotating outer ring allows the balls to roll relative to the rings, although they are in a fixed angular position. Pure rolling conditions are encountered in normal operation of rolling bearings the only difference to the present rig is the value of the entrainment velocity of the lubricant. As the entrainment velocity is the same at both contacts in both, real operating conditions and in the present arrangement, this difference does not affect the ratio of the film thickness at the inner and outer rings. One of the balls is extracted from the bearing and a central hole is drilled through. A shaft is then interference fitted to this hole such that it rotates with the ball. Slip rings are attached to this shaft thus the capacitance of the contact at the inner and outer rings can be measured separately. The material of the cage is electrically insulating in order to isolate completely the desired ball.

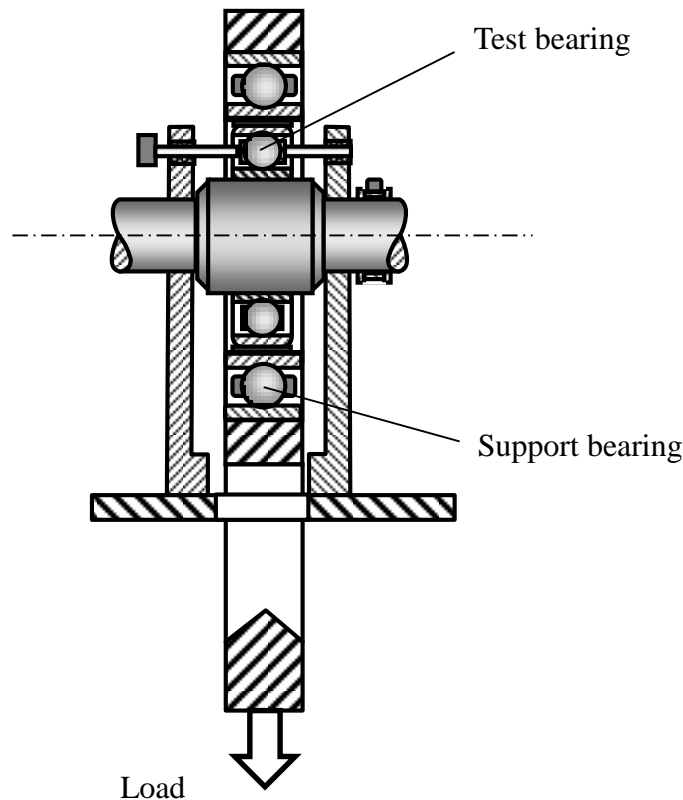


Figure 1. Detail of the testing bearing arrangement

The temperature of the rings of the test bearing was measured by thermocouples placed close to the location of the test ball. The oil used for the preliminary tests is poly-alpha-olefin (PAO4) with a viscosity of, 0.024Pas at a temperature of 30°C. To be noted that this the temperature of the bearing increased from 30°C to 34°C during the duration of the test. Few drops of oil were placed on each ring and the shaft was rotated by hand such that the oil spreads on the surfaces of the raceways and balls. The motor was then started and the capacitances of the contacts at the inner and outer rings as well as the temperatures were recorded. For the measurement of the capacitance an impedance phase – shift analyser Solartron 1260 was employed.

Results

The measured capacitance for the two rings, at a radial load on the bearing of 1000 N and a range of rotational speeds of the shaft between 240 rpm and 1020 rpm is shown in Fig. 2. It can be seen that the capacitance of the inner ring is larger than that of the outer ring, which indicates thinner film thickness for the inner ring. Also, as expected the capacitance falls with entrainment speed. Using the procedure explained in reference [17] for steel/steel contact, the film thickness was extracted from these capacitance values. The results are shown in Fig. 3. It is obvious that the inner ring film thickness is consistently smaller than the outer ring value. The difference is between 40 and 28 percent throughout the range of speeds employed. It is also to be noted that the measured film thickness is smaller than the values predicted by Hamrock and Dowson formula. At this moment it is not clear where this discrepancy comes from and it is not relevant anyway as only the difference between the inner and outer ring film thickness was sought in this paper. As far as the authors are aware this is the first paper where separate film thickness measurement in the contacts of a rolling element bearing with the inner and outer rings is reported.

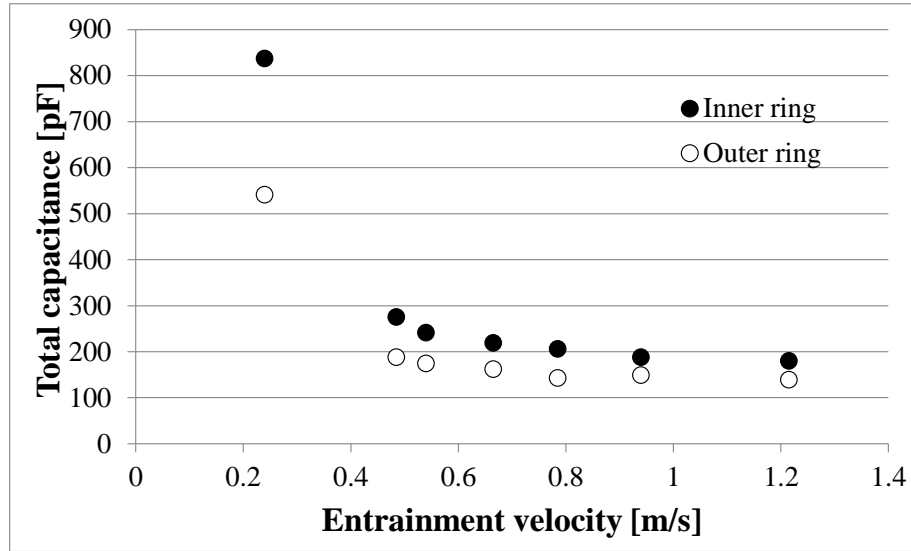


Figure 2. Dependence of capacitance of entrainment velocity

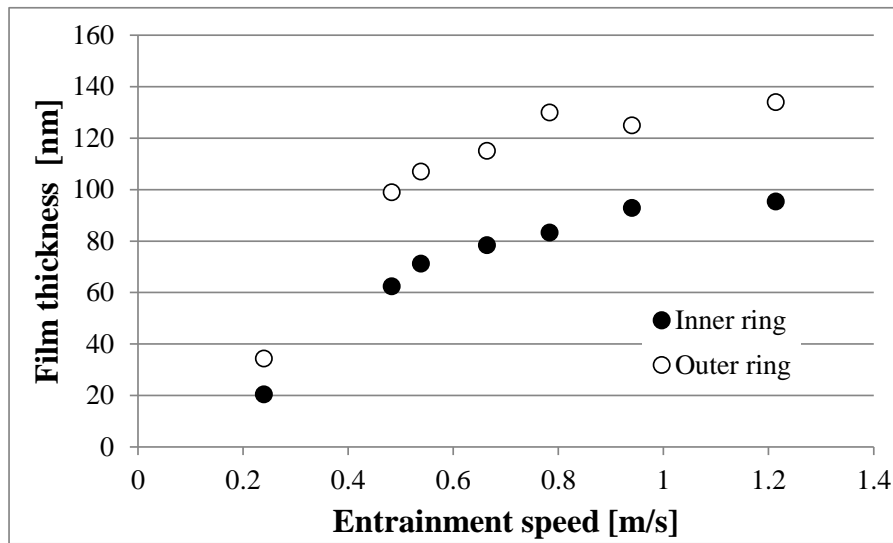


Figure 3. Difference between lubricant film thickness at inner and outer ring

Summary

A novel experimental rig for measuring the lubricant film thickness in rolling element bearings, based on electrical capacitance, has been designed and manufactured. Unlike other test rigs this is able to measure separately the capacitance of the contacts between the rolling elements and the inner and outer ring respectively. The results show that, over the range of speeds employed, the film thickness at the outer ring contact is between 28 and 40 percent larger than that at the inner ring contact. This is a first paper where measurements of the lubricant film thickness at the inner and outer rings contacts are reported. More tests are envisaged in order to extend the range of lubricants used (for example the use of grease) and to elucidate the difference observed between theoretical and measured values.

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